CHARACTERISTICS AND MODELING OF HIGH VOLTAGE PHOTOCONDUCTIVE SWITCHING DEVICES

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Introduction

Photoconductive devices have recently experienced increased popularity for a variety of applications including high voltage power modulation, pulse shaping, optical and radiation detection and high speed pulsing and sampling [1]. Knowledge of optical excitation requirements in order to obtain a desired output response is of crucial importance in many of the above applications. We have developed an accurate analytical model of the on-state behavior of these devices which takes into account all the known second order effects on mobility and carrier generation at room temperature (electric field, carrier-carrier interaction and optical reflection and attenuation with depth). This model has been experimentally verified over a wide range of incident optical excitation.

Analytical Model

For characterizing the on-resistance of photoconductive devices, the expression for resistance of a semiconductor material is used,

$$R_{on} = \frac{\rho L}{A} \qquad (1)$$

In Equation 1, L is the gap length and $A = W \cdot t$ is the cross-sectional area as illustrated in Fig. 1.
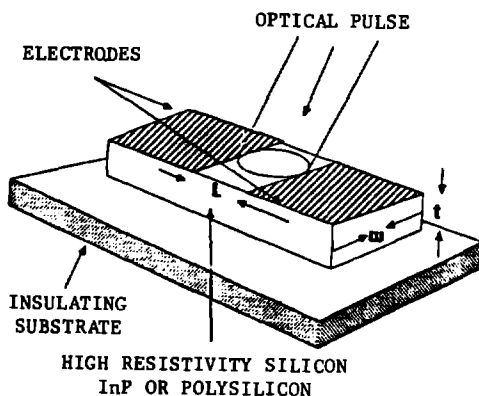

Figure 1. Photoconductive Device Structure

The resistivity is given by

$$\rho = [q \, (\mu_n n + \mu_p p)]^{-1} \qquad (2)$$

where $m_{n,p}$ are the carrier mobilities, q is the electronic charge and n,p are the photogenerated carrier concentrations. In the absence of optical excitation, the carrier concentrations are

$$n = n_0 \qquad (3a)$$

$$p = p_0 \qquad (3b)$$

which are typically near the intrinsic level for the material. Previous analysis' [1,2] have made simplifying assumptions in specifying photoconductive device on-resistance, such as constant carrier drift velocity or shallow absorption depth with respect to device thickness. These assumptions give accurate determination of photogenerated current density only under very specific conditions.

Optical Absorption

In this analysis, the optically excited carrier concentration is given by

$$p' = n' = (\frac{E_a}{h\nu})/Volume \qquad (4)$$

E_a is the optical energy absorbed within the conducting volume,

$$E_a = E_I \, (1-R) \, \exp(-\alpha y)\Big|_o^{dy} \qquad (5)$$

and $h\nu$ is the energy per photon of incident radiation, which must be larger than the bandgap energy of the semiconductor material. It is assumed that one electron-hole pair (EHP) is generated for each photon absorbed (i.e.; unity quantum efficiency).

In Equation 5, E_I is the incident optical energy, R is the reflectivity of the semiconductor material, α is the absorption coefficient for a particular wavelength of light, y is defined as the verticle distance into the device and dy represents the depth over which conduction occurs. The volume from Equation 4 is given by

$$Volume = L \cdot W \cdot dy \qquad (6)$$

For now let us assume an incident optical source with long absorption depth (i.e.; IR light, $\lambda = 1.06$ μm, $1/\alpha = 1$mm.) compared to the device thickness, which is approximately 17 mils. Under these conditions, the conduction depth dy is the same as the device thickness t, which is much less than the absorption depth. The opposite case in which the absorption depth is very shallow will be considered later. Substituting (2), (4) and (5) into Equation (1), the on-resistance of photoconductive devices is expressed by

$$R_{on} = \frac{h\nu \, L^2}{q(\mu_n + \mu_p) \, E_a} \qquad (7)$$

Note in Eq. 7, that R_{on} scales as the square of the gap length L, and is independent of device width and thickness to the first degree, two very important aspects in the design of photoconductive devices. The absorbed energy for IR light is determined by

$$E_a = E_I \, (1-R)[1-\exp(-\alpha t)] + R_B \qquad (8)$$

where R_B is the energy reflected off the backside of the switch which cannot be neglected in this calculation.

Mobility Variations

Looking at Eq. 7, if the carrier mobility is constant, the on-resistance is inversely proportional to the absorbed energy. Yet the carrier mobility is dependent on electric field and free carrier concentration. For excess carrier concentrations, $p = n \geq 10^{16}$ cm^{-3}, the mobility is severely degraded [3] as illustrated in Fig. 2. Also, with low incident

energy densities, the electric field across the device is large, then decreases as the photogenerated current increases.
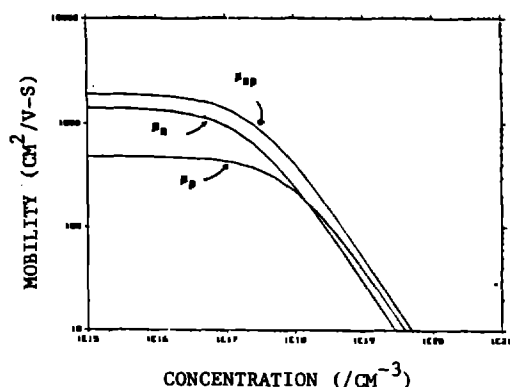

Figure 2. Mobility as a Function of
Free Carrier Concentration

Figure 4. Comparison of Switch Conductance as a
Function of Absorbed Energy for Constant
Mobility and Electric Field, Carrier
Concentration Dependent Mobility

Therefore, in characterizing the on-resistance of photoconductive devices, mobility degradation due to electric field effects [4] and carrier-carrier scattering is taken into account in the calculations. Equation 7 is simultaneously solved with the equation describing the circuit of Fig. 3. In this manner, the electric field across the device and current can be determined self consistently.
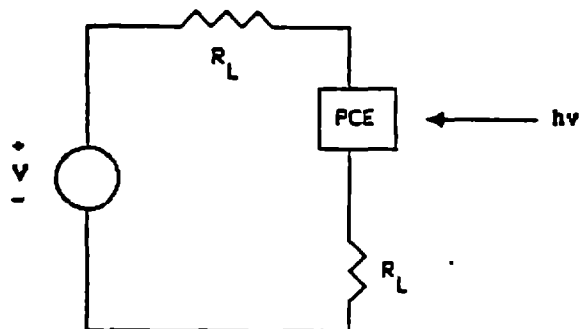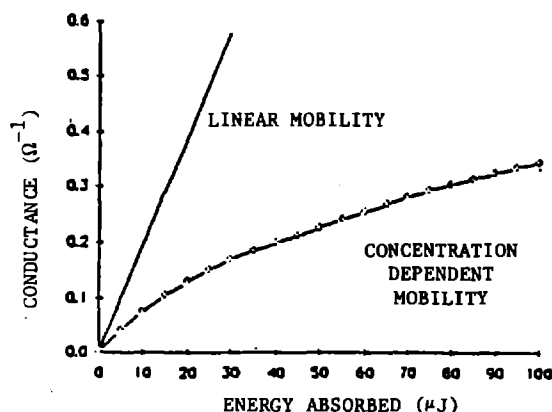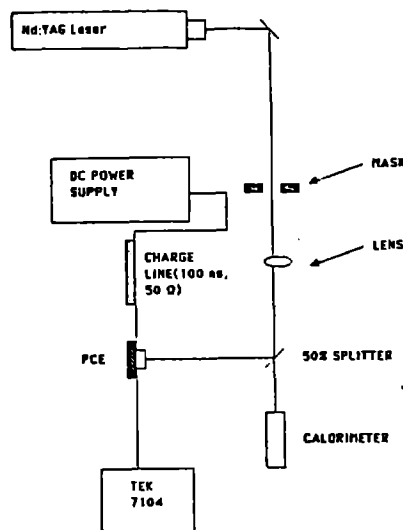

Figure 3. Equivalent Circuit of Photoconductive
Switch Mounted on 50 Ohm Transmission
Lines

To further illustrate the effects of carrier-carrier interactions, the conductance as a function of absorbed energy is shown in Fig. 4. At higher absorbed energy, the conductance begins to saturate as a result of large carrier concentrations.

Experimental Results

To verify the model we have assembled the optical setup shown in Fig. 5. This setup allows us to uniformly illuminate the gap and accurately measure the total incident optical energy into the active region of the switch. Experimental data is obtained by focusing incident light through a mask onto the gap of the photoconductive device, producing a uniform energy density on the surface. The light is directed through a 50% splitter to accurately measure the incident optical energy. The output signal is then measured on an oscilloscope for a given total input as shown in Fig. 5.

Figure 5. Experimental Setup for
Measurement of Photo
Conductive Device
On-Resistance

Results of a silicon photoconductive device with $(3mm)^2$ gap with incident IR (λ = 1.06 μm) optical energy up to 8. μJ are illustrated in Fig. 6. It can be seen that the model predicts device behavior for this case to within 10% over the entire range, and within 5% at higher energy values. Discrepancies between the model and experiment at extremely low energy densities is most likely a result of contact effects, which have not yet been included in the model. Note from Fig. 6 that at higher energy the resistance begins to saturate. Thus, silicon photoconductive device performance can be accurately predicted for a wide range of IR optical excitation energy.

Shallow Absorption

Optical sources with wavelengths which have very shallow absorption depths in the photoconductive device are used in a number of very fast switching applications. It is of interest to characterize the

absorption of incident light into the photoconductor and resulting nonlinearities caused by current crowding effects.
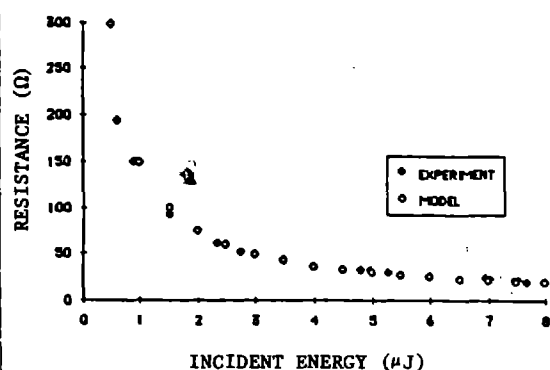

Figure 6. On-Resistance of Silicon Photoconductive Device as a Function of Incident Energy for Infrared Light on a $(3mm)^2$ Gap

For the case of green light (λ - 5300 A), the absorption depth of the device is d_e - $1/\alpha$ = 1 μm. Therefore, the incident light is totally absorbed near the surface of the device. Previously [1], the absorption depth is used in determining the resulting photogenerated carrier concentration. This assumption does not always give accurate results since the photogenerated current below this depth can be significant because of current crowding effects. To calculate the photogenerated carrier profile into the device, a discretization method is used which calculates the energy absorbed over increments which are much smaller than the absorption depth. The photogenerated currents are then summed over the entire device thickness to determine the total current. Fig. 7 illustrates the validity of this technique for the previous case of IR light.
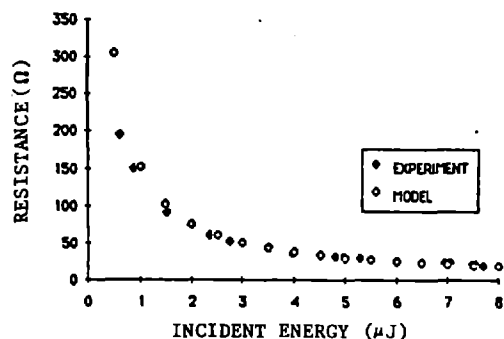

Figure 7. On-Resistance as a Function of Incident Energy for Infrared Light on $(3mm)^2$ Device Using Discretized Method to Calculate Photocurrent

The results for 5300A light are shown in Fig. 8. It can be seen that the model data does not correlate very closely to experiment. It should be noted that the variation of the two sets of data is almost exactly a factor of 2 over the entire energy range. For this data the question arises as to the validity of the measurements, or the understanding of the electron-hole pair generation process for photon energies which are much greater than the bandgap energy of the semiconductor material. For 5300 A light, the photon energy is slightly larger than twice the bandgap energy. Further study is necessary to verify both experimental results and assumptions made in the calculations.
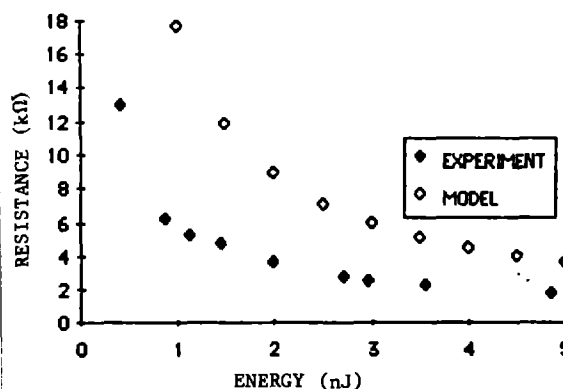

Figure 8. On-Resistance as a Function of Incident Energy for Green (532nm) Light Calculated by Discretized Method

Conclusion

A technique has been described which accurately predicts the on-resistance ($\pm$5%) of photoconductive devices for incident IR illumination over a wide range of energy. The results illustrate nonlinear regions of device operation. A model is also described to predict device performance for incident light absorbed very close to the surface with reasonable accuracy, yet further research is required to verify the assumptions made in the calculations. This work was performed by the Lawrence Livermore National Laboratory under the auspices of the U.S. Department of Energy under contract W-7405-ENG-8.

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